AD-A172 812 VORTEX LOOP DYNAMICS - A PHENOMENOLOGICAL MODEL FOR TURBULENT BOUNDARY LA (U) NOTRE DAME UNIV IN DEPT OF AEROSPACE AND MECHANICAL ENGINEERI T L DOLIGALSKI 1/1

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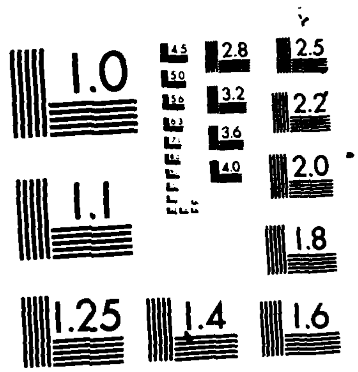

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1a. REPORT SECURITY CLASSIFICATION: Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for Public Release; Distribution Unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S): AFOSR-TR- 86-0867
6a. NAME OF PERFORMING ORGANIZATION: UNIVERSITY OF NOTRE DAME; 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION: AFOSR
6c. ADDRESS (City, State and ZIP Code): DEPARTMENT OF AEROSPACE AND MECHANICAL ENGINEERING, NOTRE DAME, IN 46556	7b. ADDRESS (City, State and ZIP Code): Same as 8C
8a. NAME OF FUNDING/SPONSORING ORGANIZATION: AIR FORCE OFFICE OF SCIENTIFIC RESEARCH; 8b. OFFICE SYMBOL (If applicable): AFOSR/NA	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: AFOSR-82-0115
8c. ADDRESS (City, State and ZIP Code): ROLLING AFB, DC 20332	10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
61 102F	2307	A2	

11. TITLE (Include Security Classification) VORTEX LOOP DYNAMICS- A PHENOMENOLOGICAL MODEL FOR TURBULENT BOUNDARY LAYER STRUCTURE (UNCLASSIFIED)

12. PERSONAL AUTHOR(S) THOMAS L. DOLIGALSKI STEPHEN M. BATILL

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
ANNUAL	FROM 1/1/83 TO 12/31/83	1984, APRIL, 1	25

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB. GR.	TURBULENT BOUNDARY LAYERS, VORTEX LOOPS

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Progess of a combined analytic/experimental study of the unsteady development of three-dimensional vortex loops in the vicinity of solid surfaces and under the influence of a crossflow is detailed. These results are important if the dynamics of the coherent structures present within the turbulent boundary layer are to be understood. it has long been recognized that the three-dimensional convecting stretching vortex loop is a major component of these flows.

In the experimental effort a new piston-orifice vortex generator and test section is described. This experimental apparatus is designed to provide reliable and repeatable vortex rings in air, which are allowed to propagate across the test section and interact with a large plexiglass plate. The rings are marked with smoke tracers by either filling the entire core with smoke, or using a smoke-wire technique. The subsequent interaction is recorded using high-speed motion picture photography. Results are given for several

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20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE NUMBER (Include Area Code)	22c. OFFICE SYMBOL
Major Michael S. Francis	202/767-4935	AFOSR/NA

DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE.

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studies: normal and oblique impacts in still air, ~~as well as~~ for oblique impacts in uniform flow.

The analytic effort ~~has been~~ devoted to improving the efficiency of the three-dimensional inviscid vortex trajectory program ~~developed~~ under the first year of the grant period. This program uses a modified Biot-Savart integration technique to consider the unsteady inviscid development of vortex structures in the vicinity of solid surfaces. Studies of normal and oblique impacts with solid surfaces under conditions of no imposed flow are detailed, as well as oblique impacts in uniform and linear shear flows.

The experimental and analytic results ~~have been~~ compared with one another and excellent correspondence between the two techniques ~~has been~~ found. These ~~synergistic~~ studies ~~seem to~~ indicate that substantial loop growth occurs due to the presence of an imposed shear, and it is this interaction between the loop and the imposed crossflow that plays a dominant role in the loop deformation process.

AFOSR-TR- 86-0887

ANNUAL PROGRESS REPORT

TO THE

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

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Grant No. AFOSR-82-0115

Vortex Loop Dynamics - A Phenomenological Model For Turbulent Boundary Layer Structure

Under the direction of

Thomas L. Doligalski, Ph.D.
Assistant Professor

Stephen M. Batill, Ph.D.
Associate Professor

Department of Aerospace and Mechanical Engineering

University of Notre Dame

April, 1984

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INTRODUCTION

The determination of the processes inherent to turbulent boundary-layer flow has long been an elusive goal for the fluid mechanist. The current study attempts to establish a phenomenological model for the regeneration process which occurs within a turbulent boundary layer. A complete cycle for this process, depicted in Figure 1, has been postulated for the purpose of reconciling the observations of many previous investigators. This cycle is composed of four steps, of which two are being studied under the auspices of this grant. A full description of this cycle has been presented in Doligalski and Batill (1983), and in the interest of brevity will not be given here.

CURRENT STATUS

During the second year of effort a great deal of time has been spent refining the techniques used to study the evolution of vortex structures. In addition, loop interaction studies relevant to turbulent boundary layers have been performed which indicate that the mean shear profile in the outer layer substantially influences the development of the loop.

Experimental Program

During the past year emphasis in the experimental phases of this program has been directed towards the continued development of the apparatus and techniques necessary to produce coherent loop structures in wall-bounded flows. The vortex generator and test section have been completed and numerous tests conducted. The tests designed to quantitatively characterize the vortex loops have been completed as well as the oblique impact studies in a stationary fluid. Considerable difficulty has been encountered in the attempts to control and quantify the loop motion in the uniform flow, or near uniform flow, near a wall. The following sections describe the modifications made to the apparatus during the past year and presents some of the results of the tests conducted to date.

Program Tasks

1) Loop Generator and Experimental Procedures

A number of significant improvements were made to the ring generator mechanism described in detail in the previous annual report. These modifications were all directed towards improving the reliability and particularly the repeatability of the "generation" process. The motor used to drive the cam mechanism has been replaced with a SCR controlled permanent magnet DC motor. This motor is capable of producing 1/8 HP with 70 in-oz of torque at 1800 rpm. The motor speed is monitored with a specially designed microprocessor counter with which the speed can be set and recorded to within +/-3 rpm. The ability to set and maintain the motor speed has improved the repeatability of the generator mechanism.

The original design of the device used to control the rotation of the cam shaft, and thus the stroke of the piston, involved two optical pickups which sensed the location of two "fins" on the cam shaft, which were used to set the start and stop locations of the cam. The alignment and setting of these fins proved to be particularly cumbersome and two new concepts were developed. The first involved a circular disk with a large number of small holes cut around its perimeter. The number of holes were sensed using an optical pickup and "counted" in order to properly position the cam. Problems were encountered with the response time of the pickups, and repeatability was degraded due to scattered light interference. Eventually this optical method was replaced with a simple timing circuit which was initiated at the beginning of the events, and then which disengaged the clutch/brake after an appropriate rotation of the cam.

Currently, the "top dead center" location on the cam is detected by a small microswitch which is triggered by a bump on the cam shaft. The formation of a single ring is initiated by depressing a button which engages the cam and starts two timing circuits. The first is used to disengage the cam and stop it after a pre-set rotation of the cam has been achieved. The second timing circuit is used to trigger the camera and strobes after a pre-set delay. This arrangement has proven to be very reliable and, as the results of the characterization studies indicates, reasonably repeatable.

Most of the original experimental studies were conducted using rings whose presence was indicated by filling the ring generator chamber with smoke so that fluid entrained from the chamber in the formation of the ring was marked. This is an easy and useful method to mark the ring in order to evaluate its overall motion, but it does present some difficulties when trying to quantify the ring motion. Using this approach the entire ring is filled with smoke and though the center of the core is void of smoke, the remaining smoke which surrounds the entire ring makes it difficult to identify the location of the core. An alternate method was developed to mark the ring which is based on the smoke-wire technique. A fine steel wire is stretched across the orifice of the ring generator. This wire is coated with a mineral oil and can be heated by passing an electric current through it. This causes the formation of fine smoke streaklines at the wire which, when synchronized with the initiation of the ring generation process, marks the fluid in the ring. This is quite similar to the use of injected dyes in water tunnel experiments. This approach has proved to be very effective and was used for all of the normal and oblique impact studies discussed in this report.

The smoke wire has also been used in two other visualization studies. The splitter plate, which is used as the "wall" for the ring interaction, has been modified so that a smoke-wire can be placed spanwise across the plate; for those tests conducted in either uniform or shear velocity profiles a thin sheet of smoke can be convected downstream along the surface of the plate. This technique is being used to examine the influence of the ring on the fluid very near the plate and may be instrumental in understanding certain aspects of the burst or loop generation process in the turbulent boundary layer. Similarly, a smoke-wire can be placed upstream of the generator in a position normal to the plate and in the same plane that the loop motion occurs. This is being done to both provide another method of visualizing the ring itself as well as to help quantify the velocity distribution along the plate. Both of these applications have been demonstrated and are currently being "perfected" so that they can be used to provide useful data. This involves coordinating the timing of the events and developing the proper lighting and photographic procedures for data collection.

2) <u>Loop Characterization - Normal Impact Studies</u>

One of the primary goals of the experimental phase of this study was to develop the capability to quantify the characteristics of single vortex loops, to provide input for the analytic studies and therefore allow for direct comparison with the numerical results. This has required the development of a very repeatable method for generating the loops (in order to be able to quantify more than single isolated events) and establishing a procedure for characterizing a given loop. Although vortex loops have been the subject of intense study for a good number of years, they still present some very difficult problems. The actual formation process is quite complex and can be influenced by a number of factors. Those which can be controlled in the current experiment are the velocity of the flow through the orifice, the diameter of the orifice and the volume of fluid which passes through the orifice. These are determined by the geometry of the cam, the speed of the motor, the angular rotation of the cam and the opening of the iris. With these selected, it is desirable to define the loop diameter, loop core diameter and the circulation.

A series of tests were conducted in an attempt to define these loop parameters as determined by the generator settings. This involved recording the position/time histories of circular loops moving normal to a solid wall in a still fluid. Prior to the viscous interaction of the ring with the boundary layer induced by the ring on the wall, there is an inviscid interaction of the ring with its image. By a least-squares fit of the analytic solution of the ring trajectory to the experimental results, the circulation and core diameter can be determined. This indirect method has distinct advantages over attempts at direct measurement such as hot-wire and LDV due to its simplicity. The experimental data was collected using the smoke wire to mark the ring and recording the trajectory with high speed motion picture photography. The motion picture records were projected frame by frame on a digitizing tablet which is part of the microprocessor-based data acquisition system developed for this effort. The position/time histories were transferred to the University of Notre Dame's IBM mainframe computer where the actual calculations were performed and the results plotted. There were initially some difficulties encountered in using this method for data reduction due to problems with the graphics tablet, but they have been resolved and these tests are complete. A "typical" experimental trajectory and fit are shown in Figure 2. The experimental data in the figure shows the locus of the centers of the core regions at the extreme ends of the circular loop for uniform increments in time. A number of loops were generated using a rather wide range of generator mechanism parameters for which laminar loops were developed. Table 1 shows the results of those tests.

These results indicate that the generator mechanism is capable of producing laminar rings which cover a range of Reynolds numbers (based on ring diameter and propagation speed) of approximately 600 to 2500. The data in Table 1 also presents the results for four different loops produced with the same generator settings, and gives an indication of the repeatability in the generation and characterization process. Future tests to evaluate the loop dynamics during both oblique impacts in still air and in wall-bounded flow will use loops generated in this range of Reynolds numbers.

Both the generation and characterization of the loop itself are areas which deserve significantly more attention, but since they are not the primary interests of this project only limited effort can be extended in this direction. It is hope that now that the loop generator exists it will provide the opportunity for further study of the physics of the loop generation. Such efforts may be instrumental in determining the origins of the loops in the turbulent boundary layer.

3) Oblique Interactions - Still Air

Using the same methods described above, a series of experiments were performed to define loop trajectories for oblique interactions of initially circular loops with solid walls. Since an "exact" solution to this interaction (even the inviscid interaction) does not exist, these results will be compared with the numerical simulations. The entire generator mechanism can be pivoted on a yoke so that the direction of propagation of the ring can be inclined up to an angle of 45 degrees with respect to the normal to the surface. The rings were marked with the smoke-wire and motion pictures of the interaction recorded. Figures 3 and 4 are for angles of 22 and 38 degrees between the normal to the plate and the direction of propagation. As with the normal impact studies, these figures locate the extreme ends of the loop in the plane in which it is moving.

As the loops approach the plate they are stretched and deformed from their circular shape. The region closest to the plate is obviously first influenced by the surface. It appears as if the radius of curvature increases in this region, and it is here where the viscous interaction appears first. The lower section is slowed, stretched and actually appears to lift-off of the surface as the boundary layer develops on the plate. Trying to describe the motion of the ring in this rather simple but three-dimensional interaction points out the greatest difficulty currently encountered in the experimental phase of this effort: that is trying to quantitatively describe this complex, three-dimensional and unsteady development of the loop structure using basically two-dimensional data acquisition methods (i.e., photography). It appears as if two alternatives exist: either three-dimensional optical techniques could be attempted, such as stereo photography, or the motion can be characterized by qualitative assessment of the entire loop behavior and quantitative measurement of the position of extreme points on the loop as has been done to date. Keeping in mind the primary goals of this study, it is apparent that the second approach is most desirable for it will provide the necessary details of the loop dynamics and allow for quantitative comparison with the numerical studies.

4) Loops in Wall-Bounded Flow

The initial efforts to study loops in wall-bounded flow were directed towards the development of facilities in which the necessary flow could be achieved. This has proven somewhat difficult due to the very low-speed flows which are needed. It appears as if coherent laminar rings can be achieved in flows where the ratio of the ring propagation speed to flow speed is on the order of one. This is apparently due to the interference of the flow with the ring generator itself, and the disturbance of the shear layer at the orifice. Since most of the loops studied to date have propagation speeds of approximately 1 ft/sec, this means it is necessary to develop steady flows in the tunnel test section of less than 3 ft/sec. This has required some modification of the existing wind tunnels. This low speed also presents considerable difficulty with regard to measuring the velocity distribution within the tunnel. Both pressure and hotwire measurements are severely limited at these low speeds, so it appears as if using the smoke-wire as a velocity probe, similar to the original work of Cornish, will provide the most reliable means of measuring the velocity and its distribution in both the "uniform" and shear profile cases.

Studies have been conducted with what was intended to be a uniform flow, and with the loop initial direction of motion towards the plate. For the proper ratio of loop to tunnel speed, the interaction of the loop with the wall results in drastic loop growth; the loop assumes a "tipped" position with its downstream head rising off of the plate and the occurrance of significant stretching. It should be noted that due to the boundary layer development on the splitter plate much of the loop is in this shear layer, so that these observed effects are most likely due to both the inviscid interaction of the loop with its image as well as with the velocity gradient in the shear layer. Current efforts are now directed at quantifying the shear layer and developing a method for photographing this stretching and convecting loop structure.

The splitter plate has also been inverted in the test section and positioned with respect to the loop generator so that rings can be convected around the leading edge of the plate as they move downstream. This positions them close to the surface and tipped with respect to the plate, with their direction of propagation away from the surface. This is similar to the orientation observed in numerous ongoing boundary-layer studies. Though there has only been limited experience with this approach to date, we have been unable to successfully position the ring close enough to the plate to notice a significant interaction in most cases; when the ring is positioned close to the leading edge of the plate there appears to be a strong viscous interaction and the loop is destroyed. This type of interaction will be the focus of much of the remaining work and we are hopeful that success can be achieved with additional experience.

Analytical Program

A majority of the past year has been devoted to the modification of the vortex loop program for greater computational speed due to limitations imposed by the University of Notre Dame's Computing Center. A great deal of effort was devoted to developing alternative computing sources. Luckily, the University recently obtained an IBM 3033U, which has a substantially faster computational speed than its previous mainframe (an IBM 370/168), and it has at last been possible to perform the necessary studies outlined under the grant proposals.

Studies of normal and oblique interactions of vortex loops with a solid surface under conditions of no imposed flow have been completed. Studies of oblique impacts in uniform and linear shear flows have also been performed. The results of these studies are detailed below.

In addition to the vortex loop trajectory studies, effort has been initiated to study the unsteady development of an impulsively-started jet in a crossflow. This study is motivated by the need to provide initial conditions for the vortex loop trajectory studies which realistically model the formation process of vortex loops in turbulent boundary layers. It is believed that the "burst", a jet-like eruption of wall layer fluid into the outer layer, is the progenitor of the vortex loop.

Program Tasks

1) Computer Program Enhancement

One major difficulty encountered during the previous year of this effort has been the inability to obtain sufficient computational time on the University's mainframe computer. In an effort to enhance the overall turnaround time of the vortex loop trajectory computer program, a number of improvements to the program have been made.

The greatest improvement in computational time was obtained by reformulating the subroutine which calculated the new core diameters at each time step (subroutine DIA). As discussed in the previous annual report, as the ring stretches the nodal separation distances increase, and the segment core diameters must decrease. The nodal positions are computed at each time step by integration of the Biot-Savart law. Under the previous formulation the core diameter was allowed to vary in a linear fashion along each segment, with the new core diameters computed at each nodal point using a successive overrelaxation iterative method with an optimal relaxation factor.

Unfortunately, even with an optimal relaxation factor the calculation of new core diameters at each time step took a great deal of computational time. In order to reduce the necessary CPU time, a new formulation for DIA was implemented; here the core diameter is assumed to be spacially constant along each segment. With this method no iteration is needed to compute the new segment core diameters, and a very substantial decrease in CPU time is realized.

Since the only place where the core diameter enters the computation occurs during the calculation of the nodal velocity induced by neighboring segments, the assumption of uniform segment diameter made in the current formulation does not significantly affect the accuracy of the final trajectories obtained. During this computation a value for only the nodal core diameter is necessary, for which a weighted average of the core diameters for the two adjacent segments is utilized.

In addition to the reformulation for the core diameters discussed above, a new optimizing FORTRAN compiler, VSFORT, which has recently been installed at the University, has been utilized to improve the computational speed. With these improvements the actual CPU time requirements of the trajectory program were decreased by a factor of 5.5. Unfortunately, at the same time that these changes were implemented, the University's IBM 370/168 reached a state of saturation due to an extremely heavy computational load from all segments of the University. Under these conditions turnaround times of two weeks for a single hour of execution (CPU) time were not uncommon (a complete trajectory run may take up to 12 hours of CPU time and cost about $3,000)!

In order to perform the necessary computations for this grant several alternative computing sources were explored, including the Aerospace Laboratory's DEC 11/23, the College of Engineering's PR1 ME 850 or IBM 4341, or finally Purdue University's CDC Cyber 205. All of these possibilities were explored, and it was decided to implement the program on the DEC 11/23, as this computer could be exclusively dedicated to the project for large periods of time (even though it was recognized that the computational speed of this machine was the slowest of all the alternatives, it was felt that physical control of the machine gave us a distinct advantage). To implement the program on the machine required the purchase of a FORTRAN compiler and some additional memory, both of which were obtained under the terms of this grant.

Just as the implementation process was nearing completion, the University obtained an IBM 3033U mainframe to replace its inadequate IBM 370/168. Because the program was successfully executing on the IBM it was felt that it was prudent to remain on the new mainframe in view of its greater computational speed and the improved access. All runs are currently being performed on the IBM 3033U, and it is expected that there should be little of the access difficulties encountered under the old IBM 370/168 (current turnaround time is about one day for one hour of CPU time).

2) Normal Ring Impact

Since an exact analytic solution to the normal ring impact problem is known in terms of complete elliptical integrals, this problem serves as a convenient test case for the three-dimensional loop trajectory program developed under this grant. Several normal ring impacts have been performed using the trajectory program, and as reported in the previous annual report the results are virtually identical to those obtained using the analytic solution. These results give some degree of confidence in the program developed here, and also serve as a test case to compare the experimental and the analytic efforts.

3) Oblique Ring Impact

Oblique impacts have been made with values of the "tip" angle (the angle between the ring's propagation direction and a normal to the plate) of 22, 45 and 68 degrees. Although all of these runs have been peformed in a quiescent medium, the results are identical to those obtained in a uniform flow when viewed in a frame of reference convecting at the crossflow velocity.

A typical trajectory is shown in Figure 5, for a tip angle of 22 degrees (this figure corresponds with Figure 3, which was obtained experimentally). In this figure only the points in the plane of symmetry are plotted, although there were 122 points around the loop. As expected the ring approaches the wall, undergoing slight stretching. The lower part of the ring interacts with the wall first, which slows its approach and reverses its direction. Notice that the trajectory appears to have a number of "wiggles" in it at this time:

these are due to an inadequate time step and are characteristic of this type of calculation when the vortex structure is extremely near the wall and its image-induced velocity is very large. Further refinement of the time step at this point is impractical because of the large computational times (at this point the non-dimensional time step was 0.01, and the terminating time value was a non-dimensional time of t = 10). It should be remarked that it is precisely at this point in time and space that an interaction with the viscous layer on the wall is expected, destroying this part of the loop or altering its trajectory. Because this part of the loop is located furthest from the "head" of the loop, it is expected that these "wiggles" will not immediately affect the trajectory at the "head" position of the loop. However, eventually these disturbances will propagate to the "head"; in addition, the head soon approaches close enough to the wall so as to encounter large image-induced velocities which cannot be handled without further decreases in the computational time step. It should be noted that to this point in the integrations not a significant amount of stretching has occurred, which is further corraborated by the experimental observations.

4) Oblique Ring Impact - Shear Flow

Since the mean velocity profile in the outer layer of a turbulent boundary layer may be closely modeled by a linear shear profile, vortex ring simulations were performed with the ring immersed in a region of linear shear in order to simulate the environment experienced by the vortex loop. It should be noted that a linear velocity profile is the easiest shear profile to implement because of its corresponding uniform vorticity distribution: more complex shear profiles would affect the Biot-Savart integration in an undesirable fashion. It should also be recalled that, with suitable averaging, a "hairpin" vortex loop can create a region of linear shear much like that encountered in the outer layer (see Doligalski and Batill, 1983). The zero pressure gradient data of Anderson, Kays and Moffat (1972) suggests a shear profile of slope 35% (see Doligalski, Smith and Walker, 1980, for details) which was utilized for this study.

A typical trajectory is shown in Figure 6, which corresponds to an initial tip angle of 45 degrees. As in Figure 5 only the points in the plane of symmetry are plotted, and there were again 122 points around the loop. Although the loop approaches the wall in a similar manner to that experienced during the simulations detailed above, substantial stretching of the loop occurs due to the imposed shear velocity. Note that Figure 6 represents a terminal non-dimensional integration time of $t = 4.75$, which is roughly half that depicted in Figure 5; yet the streamwise scale of Figure 6 is approximately twice that of Figure 5. The streamwise stretching due to the shear thus plays a dominant role in the loop deformation process.

5) Vortex Loop Visualization

Although vortex loop trajectories such as those depicted in Figure 5 and 6 give some idea of the loop development, they represent only two points around the circumference of the loop and thus provide only limited information about the loop shape. In order to better assess the spatial development of the loop a PASCAL program written for the APPLE IIe purchased under this grant is under development. This program utilizes high resolution graphics to plot the loop on the CRT; input to the program from a joystick enables the user to rotate his viewpoint so as to obtain a better understanding of the three-dimensional character of the loop. One task to be performed within the next few months is to utilize the program to obtain time-sequences of the loop development from various view angles in order to qualitatively assess the ring deformation.

6) Unsteady Jet in a Crossflow

One of the goals of the current effort is to investigate the mechanism whereby a small vortex structure created during the bursting event may grow into an intermediate or large-scale structure such as that observed in the outer layer. On a practical basis such growth is necessary in order for the turbulent boundary layer to be maintained, since the only source of vorticity in this flow is the wall layer, which is dominated by viscous forces. The only experimentally observed interaction between the inner and outer layers occurs during the burst, when a jet-like eruption of rotational inner-layer fluid into the faster-moving fluid of the outer layer is overturned into a new vortex structure. In order to investigate this portion of the bursting event, as well as to provide a realistic initial condition for the analytic vortex loop simulations described above (where now the loop's self-induced velocity is away from the wall) a simulation of the burst is being studied under this grant.

In the study of Doligalski, Smith and Walker (1980) a mechanism was studied which may explain the genesis of the burst. This study suggested that the burst may be the response of the inner layer to the "lifting" action of an outer-layer vortex structure. Ultimately, the inner layer responded to the action of the outer-layer vortex by a jet-like eruption of inner layer fluid into the outer layer, in an event qualitatively similar to the burst. Unfortunately, since this study was performed using the boundary-layer approximation, the interactions had to be terminated at this point because of the subsequent viscous-inviscid interaction. It was hypothesized that this jet-like eruption would be overturned into a new vortex structure by the faster-moving crossflow.

In order to learn more about this event, a new study was initiated under this grant to consider the unsteady overturning of a viscous jet in a laminar crossflow. This study is being performed using three different methods, all of which are currently under investigation: (a) an analytic study using the method of matched asymptotic expansions and valid in the limit of small jet ejection to crossflow velocities (which appears to be the correct physical limit), (b) an experimental study of an impulsively started jet, and (c) an analytic study using the full Navier-Stokes equations. Because these studies are not the major thrust of this effort, relatively little resources have been expended on this phase, which is being performed by two graduate students. This study has been ongoing for less than a year, and there have been few results to date; it is hoped that this summer will provide the students more time to finish this phase of the study.

REFERENCES

1. Anderson, P.S., Kays, W.M., and Moffat, R.J., "The Turbulent Boundary Layer on a Porus Plate: An Experimental Study of the Fluid Mechanics for Adverse Free-Stream Pressure Gradients," Thermosciences Division, Department of Mechanical Engineering, Stanford University, Rept HMT-15.

2. Doligalski, T.L. and Batill, S.M. (1983), Annual Progress Report, "Vortex Loop Dynamics - A Phenomenological Model for Turbulent Boundary Layer Structure," AFOSR-82-0115.

3. Doligalski, T.L. and Batill, S.M. (1983), Renewal Proposal, "Vortex Loop Dynamics - A Phenomenological Model for Turbulent Boundary Layer Structure," AFOSR-82-0115.

4. Doligalski, T.L., Smith, C.R., and Walker, J.D.A., "Production Mechanism for Turbulent Boundary-Layer Flows," in Viscous Flow Drag Reduction, G.R. Hough, ed., Prog. in Astro. and Aero., Vol. 72, pp. 47-72.

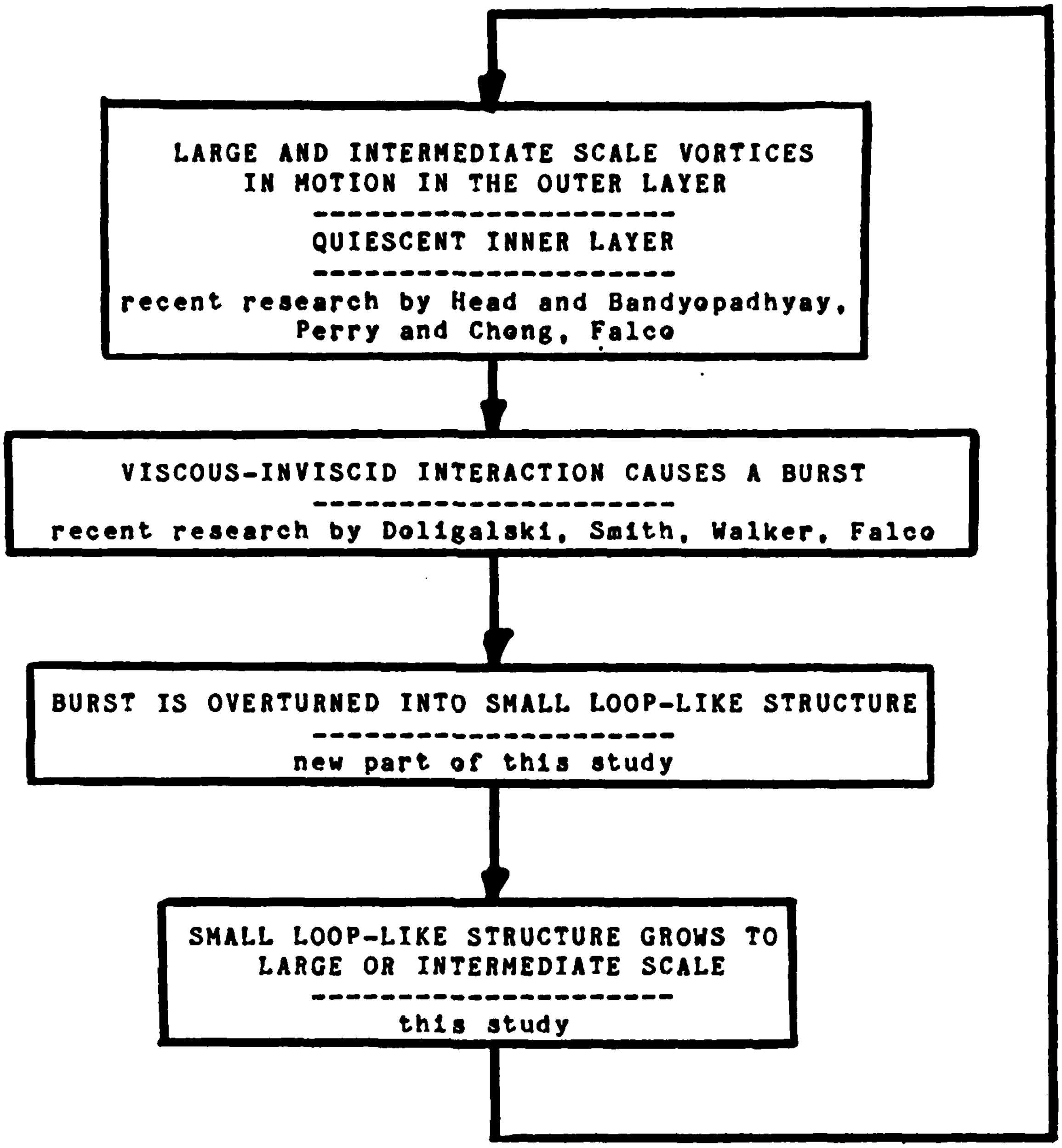

Figure 1. Proposed Turbulence Regeneration Cycle.

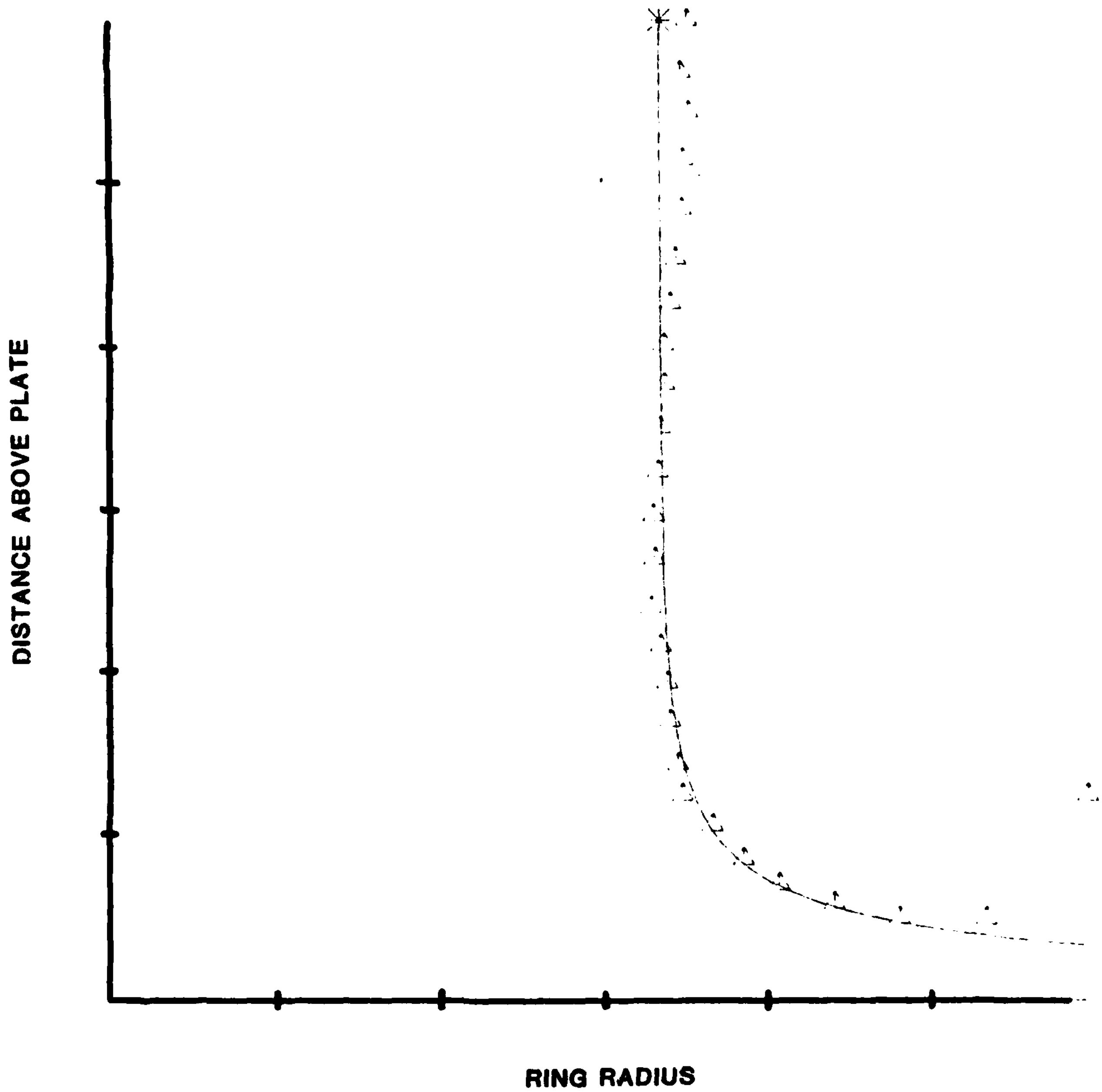

Figure 2. Experimental Normal Ring Impact Trajectory and Analytic Fit Result

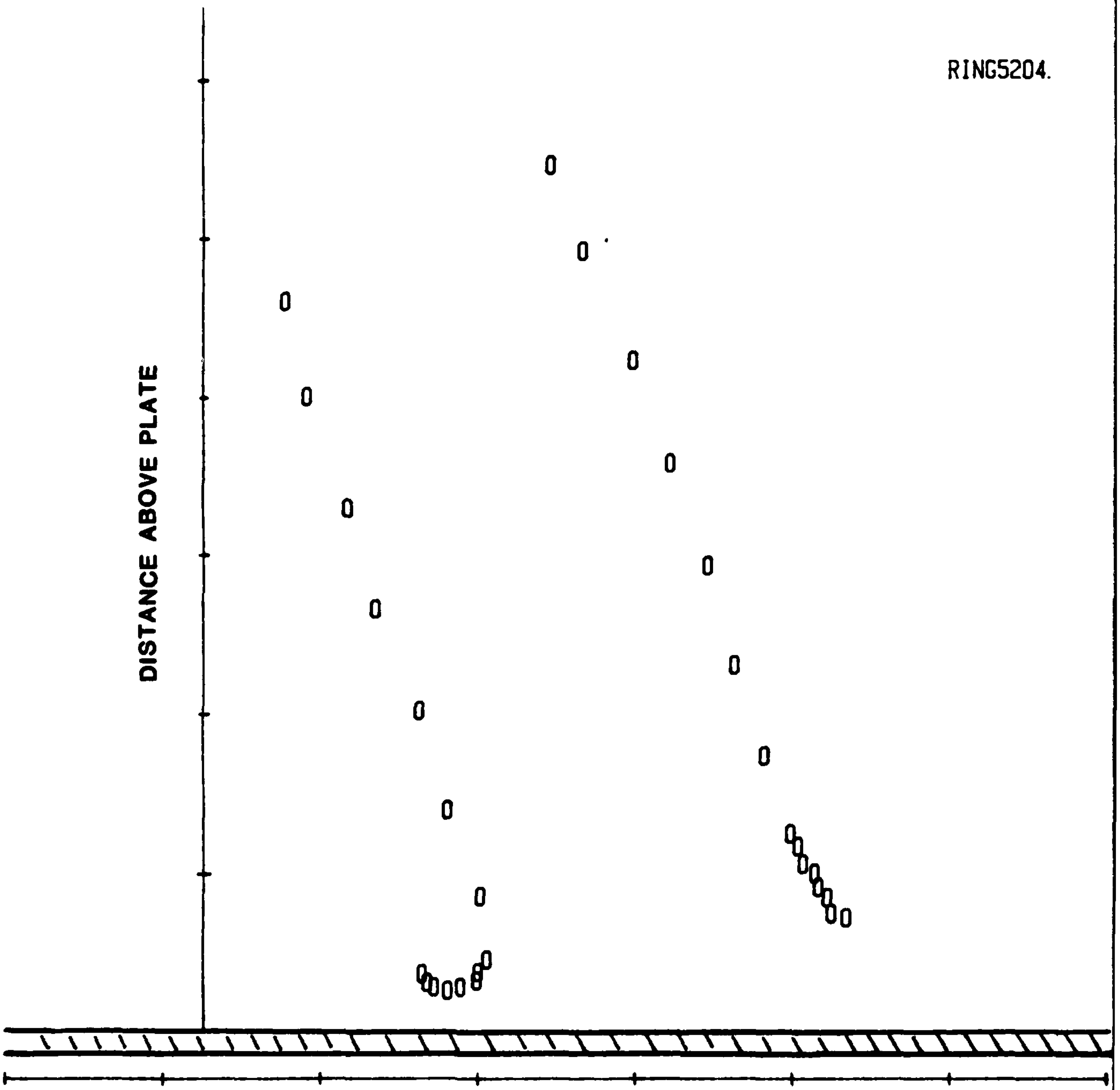

Figure 3. Oblique Ring Impact, Experimental Results $\theta = 22°$

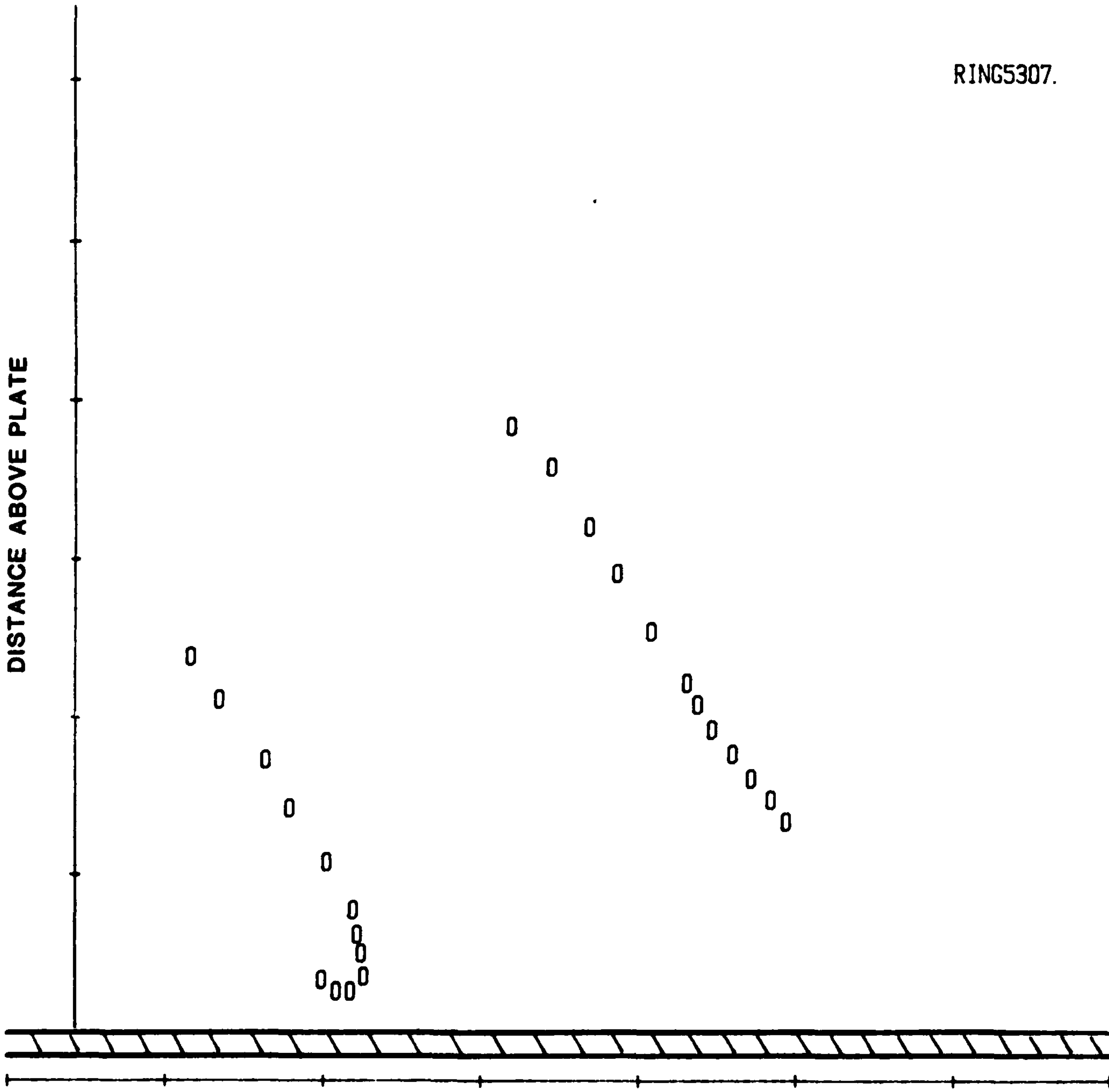

Figure 4. Oblique Ring Impact, Experimental Results θ = 38°

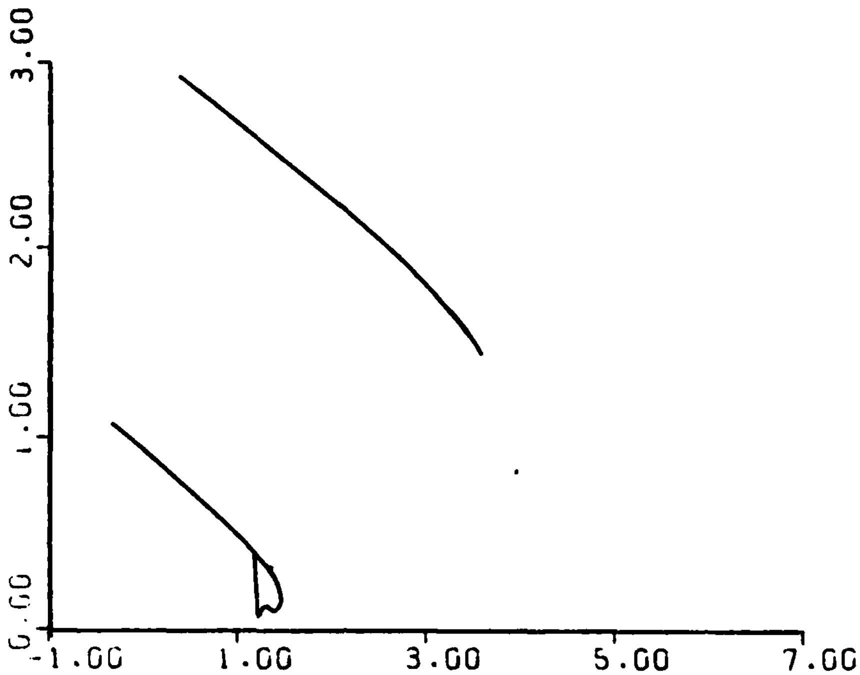

Figure 5. Oblique Ring Impact, Analytic Results
$\theta = 68°$

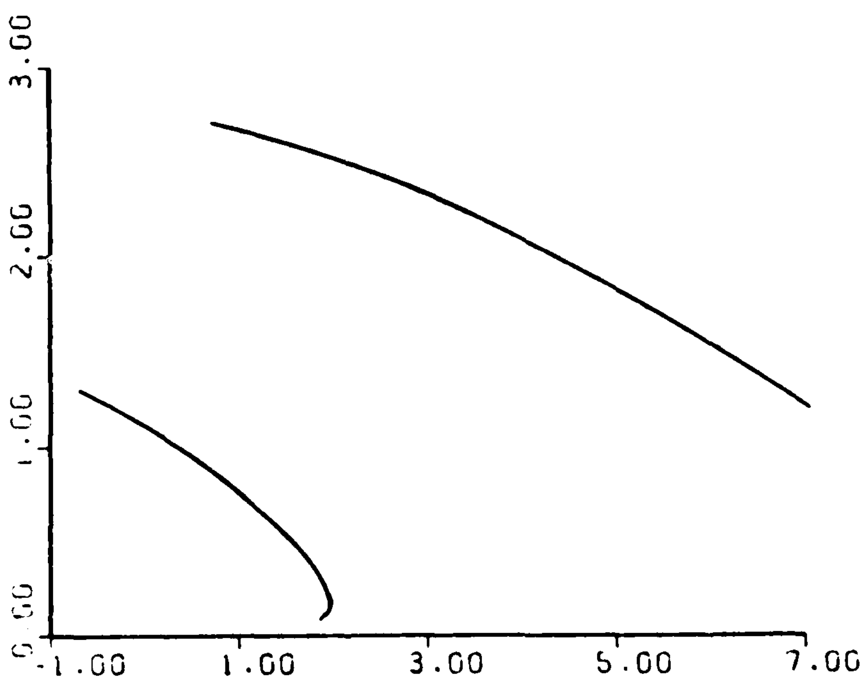

Figure 6. Oblique Ring Impact in Shear Flow, Analytic Results
$\theta = 45°$

Loop Identifier	Cam Rotation (deg)	Orifice Diameter (in)	Circulation (in^2/sec)	Loop Radius (in)	Core Radius (in)
4506	45°	2.5"	64.1	1.20	.16
4507	45°	2.5"	67.2	1.24	.22
4508	45°	2.5"	72.3	1.14	.22
4405	90°	2.5"	102.7	1.37	.34
4406	90°	2.5"	101.0	1.37	.31
4407	90°	2.5"	100.1	1.38	.32
4601	90°	2.5"	97.4	1.30	.31

TABLE I. Sample Results for Experimental Normal Impact Studies

END

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